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Does Light Control Algal Abundance in Large River Systems?

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A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science at Virginia Commonwealth University.

by

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Abstract

Title of Thesis: DOES LIGHT CONTORL ALGAL ABUNDNACE IN LARGE RIVER SYSTEMS?

By Amy Kathleen Macdonald, M.S.

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science at Virginia Commonwealth University.

Virginia Commonwealth University, 2008

Major Director: Paul Bukaveckas, Associate Professor, Department of Biology

A limited amount of research has been done to investigate the factors influencing algal abundance in large river systems. This study examines light as the primary factor that controls algal abundance in the Upper Mississippi, Missouri and Ohio Rivers. Data were collected for 2004 in conjunction with the Environmental Monitoring Assessment Program- Great River Ecosystems EMAP-GRE project using EPA approved methods. Chlorophyll a concentrations were 34.6 $\mu g \bullet L^{-1}$ in the Upper Mississippi, 19.8 $\mu g \bullet L^{-1}$ in Missouri River and 9 $\mu g \bullet L^{-1}$ in the Ohio River for 2004. Chlorophyll a concentrations were significantly different among the three rivers ($p<0.0001$) but not between years. Inter-river variation could be loosely correlated with light availability: mean Average Irradiance Dosages, which consider factors that affect light climate (depth, transparency, velocity,

surface irradiance), by river corresponded with mean chlorophyll a levels by river. Intra-river variation seemed to be due to both the influence of light and nutrients.

Introduction

To understand primary production is to understand the nutritional foundation of higher trophic species, and therefore be able to better manage increasing human impacts on ecosystems. In terrestrial ecosystems primary production is the energy source supporting higher trophic levels. Aquatic systems are more complex in that both allochthonous (from terrestrial systems) and autochthonous (production that originates in the aquatic ecosystem) inputs contribute to the support of higher trophic levels. Furthermore, the relative importance of these two inputs can vary greatly between and within aquatic ecosystems. In lakes, autochthonous inputs typically contribute a large fraction of the energetic support for higher trophic levels (Lindeman 1942). In rivers, allochthonous inputs contribute the majority of organic matter inputs (Vannote et al. 1980), leading many to question the importance of primary production to consumers in theses ecosystems.

There is a growing body of literature supporting the hypothesis that primary production is disproportionately more important in supporting riverine consumers than its quantity suggests. Thorp et al. (2002) found that although autochthonous organic matter was less plentiful, it was more labile than allochthonous organic matter and therefore important in supporting riverine consumers. Guelda et al. (2005) found that the algal fraction of particulate matter was a significant factor predicting *Bosmina* population growth rates,

suggesting that autochthonous inputs were important to riverine consumers. Similarly, Rutherford et al. (1995) reported that fish growth in the lower Upper Mississippi was dependent on autochthonous production, not floodplain inputs. Stable isotope and production data have indicated that in the Orinoco River phytoplankton and periphyton are the ultimate C source for most invertebrates and fish even though allochthonous inputs comprised more than 98% of potentially available carbon (Lewis et al. 2001). More generally, these studies found that although food quantity is higher in systems dominated by allochthonous inputs, the quality of the food is much lower than that which results from autochthonous production (Thorp and Delong 2002). Because primary production is an important aspect of riverine food webs, I undertook a study that explored factors controlling primary production in riverine ecosystems.

Constraints on primary production in aquatic ecosystems are light, nutrients, temperature, and grazers (zooplankton and benthos). The relative importance of these factors varies between and within aquatic ecosystems. In lentic systems, nutrient limitation is favored by low turbidity (higher light availability), high residence times (ca. months-years) and low nutrient inputs from exogenous sources. Lotic, or flowing systems, such as rivers, usually have shorter residence times (ca. days-weeks) and are typically nutrient rich, particularly in regions where human land-use predominates. In addition, rivers have high velocities that keep particulate matter suspended in the water column,

decreasing light availability and causing primary production to be light limited (Sellers and Bukaveckas, 2003).

Light conditions experienced by riverine phytoplankton are determined by water transparency, incident solar radiation and depth. Light attenuation in water is determined by the amount of light that is scattered and absorbed. The depth to which light can penetrate the water column is therefore dependent upon both particulate and dissolved substances. The photic zone, or zone where the light is great enough to support photosynthesis in excess of respiration, varies depending on the clarity of the water. Unlike lakes, rivers are well-mixed systems, where particles spend an equal amount of time at every depth. If the photic zone is large relative to the overall depth of the water column, then it can be assumed that photosynthesis will exceed respiration. Conversely, if the photic zone is small, respiration will dominate. Therefore, the deeper the river, the greater the photic zone must be in order to support net primary production. Additionally, residence time can affect light utilization by phytoplankton. Higher water velocities reduce the amount of time phytoplankton spend within a specific reach thereby reducing the potential for biomass accrual.

Rivers that have water regulation structures, such as dams and impoundments, exhibit reduced velocity relative to those that are naturally flowing. Changing the velocity of a river can change the clarity of the water, therefore altering the light

climate for primary producers. Dams affect the light climate of rivers not only through their effects on sediment loads and water transparency but also by altering the depth of the channel. Both light and nutrient limitation may occur under these conditions and their importance may vary spatially depending on flow regulation (Koch et al. 2004). Sellers and Bukaveckas (2003) designed a hydrodynamic-based model to predict variation in primary production arising from both seasonal changes and regulation structures in the Ohio River. This model predicted chlorophyll values to within 1 mg m^{-3} of observed values, showing the impact that hydrologic factors have on algal abundance.

This study evaluated the controls on phytoplankton abundance in three large river systems: the Upper Mississippi, Missouri and Ohio. We hypothesized that light was the primary factor that controlled algal abundance in these three rivers.

Methods

Study Sites

Data for this study were collected as part of the EPA Environmental Monitoring and Assessment Program for Great Rivers Ecosystems (EMAP-GRE). All parameters were analyzed for 2004, but chlorophyll a data were analyzed for 2004 and 2005 in order to determine inter-annual variability within rivers. The Ohio, Upper Mississippi, and Missouri Rivers comprise the study sites for this research. The entire Ohio and Missouri Rivers were included in the sampling area. The Upper Mississippi River was studied only upstream of its confluence with the Ohio River. The rivers differ in a number of features that influence conditions for algal growth (Table 1). Important differences include hydro geomorphology (discharge, channel depth, human engineering), water chemistry (nitrogen and phosphorus concentrations), and land use. The Ohio River exhibits the highest annual discharge which exceeds that of the Upper Mississippi and Missouri combined. The Upper Mississippi River has the highest agricultural land use (70%) and the highest average nutrient concentrations (total nitrogen: 2.4 $mg \cdot L^{-1}$, total phosphorus: 0.17 $mg \cdot L^{-1}$). The Ohio River has

intermediate land use by agriculture (48%) and also intermediate nutrient concentration (total nitrogen: 1.3 mg•L^{-1}, total phosphorus: 0.08 mg•L^{-1}). The Missouri River has the lowest basin area used by agriculture (33%) and the lowest nutrient levels (total nitrogen: 1.0 mg•L^{-1}, total phosphorus: 0.18 mg•L^{-1}). The rivers also differ in the extent to which humans have altered their flow regime. The Missouri River has few but very large dams whereas the Upper Mississippi and Ohio Rivers have a large number of smaller dams. High dams create impoundments where sediment and nutrients are retained (Vorosmarty et al. 2000). Low dams have modest effects on flow regime and sediment and nutrient retention (Sellers and Bukaveckas 2003).

Sampling Design

A probability-based sampling design was used to allow for statistical inferences for the target population. Sampling sites were chosen randomly for each of the three rivers (Schweiger et al. 2005). Large impoundments on the Missouri River were excluded because the focus of the study was on characterizing flowing waters. Samples were collected between July and October to characterize river conditions during warm-water base-flow period. In 2004, a total of 320 sampling sites were visited which included 90 sites on the Ohio River, 94 sites on the Upper Mississippi River and 136 sites on the Missouri River. In 2005, there were a total of 194 sampling sites with 62 on the Ohio River, 56 on the Upper Mississippi River and 76 on the Missouri River.

Sample Collection

A wide range of metrics were measured as part of the EMAP-GRE project including water quality parameters, habitat analysis and living resources (plankton, macroinvertebrates, and fish). My thesis focuses on river characteristics relevant to assessing algal abundance (i.e. chlorophyll concentrations) and controlling factors (measures of light and nutrient availability). Relevant data included measures of channel depth, water velocity, nutrient concentrations and water clarity. For each sampling site three stations were established: one at the main channel, one half-way between the main channel and each river bank. Samples are taken from three depths at each station: 0.5 m from the surface, mid depth, and 0.5 m from the bottom. A composite sample was then obtained by pooling water from the three depths and three sampling stations. Sample analysis included chlorophyll-a, turbidity, and nutrient concentrations (Angrandi et al. 2006). In addition, depth and width of the river was recorded.

Sample Analysis

Samples for CHLa analyses were for filtered in the field and shipped frozen to a central facility (University of Louisville Environmental Analyses Laboratory). Depending on suspended sediment concentrations, between 200 and 1,000 ml of river water were filtered through a 0.5-mm glass fiber filter (Gelman A/E). Chl *a*

was extracted in 90% buffered acetone, and concentrations were determined by fluorometry using a Turner Designs 10-AU fluorometer with acid correction following U.S. EPA standard method 445.0, revision 1.2 (Arar and Collins 1997). Turbidity and nutrient analysis was done per approved EPA protocols.

Analytical Methods

The discharge calculations (explained below), coupled with transparency levels and velocity, aided us in calculating values that characterized the light climate at each sampling site. Average Irradiance (AI) was calculated from Kd, average depth and an assumed incident light value (2000 µmol photons) using the following equation:

$$AI = \text{incident light} / (Kd * \text{mean depth})$$

An AI dosage was then calculated by using the equation AI dosage = AI /velocity, resulting in an estimate of the amount of light that is received by an algal cell during transit over a fixed interval of distance (Figure 1). I used turbidity values to estimate the light attenuation coefficient (Kd) from the following formula:

$$Kd = 0.0646 * \text{turbidity} + 0.6697 \text{ (Kalff, 2002).}$$

I also calculated Kd from secchi values and found similar results so hereafter I will use only turbidity derived values. From Kd, I determined photic depth of the sampling site. Because depth determines the average irradiance experienced by phytoplankton in a well-mixed water column, Kd and average cross-sectional depth were used to characterize the light conditions at each sampling location.

To determine average cross-sectional depth I used depth measurements taken at the three sampling locations at each sampling site.

Discharge was used to calculate water velocity in order to better evaluate the changing light climate of the river. River discharge at time of sample collection was estimated using data from nearby gauges. Discharge values were obtained from USGS and USACE gauging stations for the day of sample collection. The purpose of calculating discharge as close to each sampling site as possible was to characterize the light climate at each site and to explore its relationship to chlorophyll a levels. I used river discharge, retrieved from USGS and USACE databases, and cross-sectional area to estimate velocity at each sampling location. Discharge values for each sampling site were calculated using the following stipulations: 1) If a sampling site was within 40 km of a gaging station, the discharge of the gaging station was used. 2) If there was no gaging station within 40 km of the sampling site, a discharge value was interpolated by using the closest upstream and closest downstream gaging station. 3) If there was a major tributary between an upstream gaging station and a sampling site, the flow contributed by the tributary was added to the sampling site discharge approximation. On average the distance between a sampling site and the nearest gaging station was 60 km on the Upper Mississippi River, 56 km on the Missouri and 82 km on the Ohio River.

Results

Chlorophyll concentrations varied both between and within the three rivers. In 2004, The Upper Mississippi River had chlorophyll levels that averaged 34.6 $\mu g \cdot L^{-1}$, though they ranged from 0 to 80 $\mu g \cdot L^{-1}$ over the length of the river. The chlorophyll levels in the Missouri River averaged 19.8 $\mu g \cdot L^{-1}$, with a peak in the lower river (river mile 400-600) where values reached 50 $\mu g \cdot L^{-1}$. Besides the peak of high values in the Missouri, no longitudinal trends were observed (Figure 2). The Ohio River differed greatly from both the Upper Mississippi and Missouri, most notably in its very low chlorophyll levels (average= 9 $\mu g \cdot L^{-1}$) (Figure 2). River chlorophyll levels between 2004 and 2005 showed little inter-annual variation. The CHLa of the Upper Mississippi River was 35.6 $\mu g \cdot L^{-1}$ in 2004 and 35.2 $\mu g \cdot L^{-1}$ in 2005, a difference of less than 2%. The CHLa of the Missouri River was 19.8 $\mu g \cdot L^{-1}$ in 2004 and increased by 11% to 22.0 $\mu g \cdot L^{-1}$ in 2005. The Ohio showed a 5% difference in average chlorophyll values from 8.4 $\mu g \cdot L^{-1}$ in 2004 to 8.0 $\mu g \cdot L^{-1}$ in 2005. Additionally, two-way ANOVAs showed that there was no significant difference between years for the three rivers (Table 3). Thus

inter-river differences in chlorophyll were consistent across the two years of the study.

Temporal and spatial patterns of CHLa were determined for each of the three rivers. Figures 3 and 4 represent sampling dates for 2004 and 2005 versus river mile with attention given to the approximate chlorophyll level found at each sampling site. The Missouri River in 2004 showed clear spatial patterns in chlorophyll concentrations; between river mile 200 and 700 concentrations were higher than up or downstream. The Upper Mississippi and Ohio Rivers showed no strong spatial or temporal patterns in 2004. 2005 showed clear temporal patterns in all three rivers. Each river shows higher chlorophyll concentrations after mid-August.

Inter-river differences in CHLa generally followed inter-river differences in nutrient concentrations. Most notably, the Upper Mississippi River exhibited higher concentrations of SiO_2, $N\text{-}NO_3$, and TN than both the Ohio and Missouri. For the Upper Mississippi River, the only values that were significantly correlated to CHLa are those for SiO_2 and SRP (Table 3). The Missouri River had significant correlations between CHLa and TP, SRP, TN, and Cl^-. The Ohio River chlorophyll values were significantly correlated with TP, SiO_2, TN, and NO_3. The strongest correlation was between the chlorophyll and Cl^- in the Missouri River.

Because we were interested in the possibility of light being one of the major controlling factors of algal abundance, and river depth, velocity and clarity can affect light availability, a close investigation into these variables was necessary. The mean depth of the Ohio River (6.1 m) was almost twice as deep as the Upper Mississippi (3.9 m) and Missouri (2.7 m). Both the Upper Mississippi and Missouri increased in average depth towards the mouth whereas the Ohio River was more variable and showed no consistent pattern (Figure 5). To characterize the light climate of the three rivers, we derived an estimate of the light attenuation coefficient (K_d) based on measured values of turbidity. The average K_d values were 3.4 m^{-1} for the Upper Mississippi, 5.4 m^{-1} for the Missouri and 2.1 m^{-1} for the Ohio, indicating that the Ohio was the most transparent and the Missouri the least transparent (Figure 6). Differences between the three rivers K_d values were significant (Table 3). The variation within the Upper Mississippi was low with only several sampling sites indicating K_d values higher than 5 m^{-1} whereas the Missouri varied greatly near the mouth and less so upstream. The Ohio varied the least with all values below 5 m^{-1}. Overall, inferred light attenuation coefficients were generally low (K_d < 3 m^{-1}) with few values in the Upper Mississippi and Missouri above 5 m^{-1}.

The light environment experienced by phytoplankton in a well-mixed water column is determined not only by light attenuation but also by the depth to which cells are mixed. The average irradiance (AI) within the water column was

calculated to take into account intra- and inter-river variation in channel depth. Average irradiance (AI) values differed significantly between the three rivers with the Upper Mississippi at 270 µmole photons•s^{-1}•m^{-2}, the Missouri at 490 µmole photons•s^{-1}•m^{-2}, and the Ohio at 200 µmole photons•s^{-1}•m^{-2} (Figure 7 and Table 3). The average irradiance was consistent throughout the length of the Upper Mississippi and Ohio whereas it was more variable towards the headwaters of the Missouri. The Ohio River, despite its higher transparency (low K_d), exhibited poor light conditions (low AI) due to its great depth. Despite the low transparency of the Missouri River (high K_d) it demonstrated good light conditions (high AI) due to its shallow depth. The Upper Mississippi River showed moderate depth and transparency with a corresponding moderate quality of light availability.

The amount of light experienced by phytoplankton within a given reach is determined by the average irradiance and the length of time that cells are resident within that reach. The velocity of a river determines how long cells are within a particular reach. The mean velocity for the Missouri River (1.16 m•s^{-1}) was nearly twice as much as the mean velocities of both the Ohio (0.62 m•s^{-1}) and the Upper Mississippi (0.68 m•s^{-1}) rivers. Both the Upper Mississippi and Missouri showed a trend of increasing velocity nearing the mouth of the river whereas the slower Ohio River was less variable and showed no trend in relation to river mile (Figure 8). For the Upper Mississippi, Missouri, and Ohio the AI dosage values were 1.0, 0.6, and 0.4 mole photons•m^{-2}•km^{-1}, respectively (Table

3). The Ohio River showed much the same pattern as it did for AI: consistently low. The Missouri and Upper Mississippi Rivers showed higher average irradiance dosage values towards the headwaters with extremely poor light conditions (low AI dosage) towards the mouth due to increasing depth (Figure 9) and increasing velocity (Figure 8). Due to the great depth of the Ohio River, AI dosage stays consistently low.

Discussion

Chlorophyll a concentrations can vary greatly among rivers. The Upper Mississippi, Missouri and Ohio Rivers exhibited a large range of CHLa values that was comparable to that observed among rivers worldwide: 1-5 $\mu g \cdot L^{-1}$ in the Lawrence River (Basu et al. 2000); 0.8-2.2 $\mu g \cdot L^{-1}$ in the mainstem of the Cinaruco River, Venezuela (Cotner et al. 2006); 1-36 $\mu g \cdot L^{-1}$ in the Cape Fear River (Kennedy and Whalen 2008); 7-27 $\mu g \cdot L^{-1}$ in the Murray River, Australia (Roderick and Merrick 2006); 121-162 $\mu g \cdot L^{-1}$ in the Trent River, England (Skidmore et al. 1998).

Inter-river variation

Major differences were observed among between the three rivers in their depth, transparency, and chlorophyll levels. Many studies point to light availability as the key factor that determines algal abundance (Hudon 2000, Kennedy and Whalen 2008, Knowlton and Jones 2000, Leland et al. 2001, Roderick et al. 1995, Whalen and Benson 2007) where others point to both nutrient and light limitation (Miltner and Rankin 1998, Basu et al. 2000, Koch et al. 2004). Numerous

aspects of a river's composition (including: geographical location which can control surrounding land use and climatic factors; river morphology; and allochthonous inputs) which can determine the type of carbon and nutrients available for algal use determine the limiting factor of algal production. Ohio is the deepest river, followed by the Upper Mississippi and then the Missouri. What is often expected is that the deeper the river, the greater the aphotic zone, and the lower the algal productivity (Retamal et al. 2007). For these three rivers however, that is not the case: the Upper Mississippi had the highest mean chlorophyll level, followed by the Missouri and then the Ohio. Other factors such as turbidity and velocity influence the light available for photosynthesis.

The mean AI dosage seemed to be the best predictor for algal abundance, in that the higher the AI dosage of the river, the higher the mean chlorophyll value. The Upper Mississippi had the highest mean chlorophyll and AI dosage value, followed by the Missouri and Ohio. The Missouri's lower AI dosage value was likely due to increased velocity. Increased velocity results in lower AI dosage values because phytoplankton spend a shorter amount of time within a specified reach. The Upper Mississippi, on the other hand, had the highest chlorophyll values. Its clarity, shallowness and slower mean velocity likely led to the higher light availability needed to support high algal growth.

Hudon (2000) suggested, through studies of the St. Lawrence River, that chlorophyll levels can be greatly influenced by morphological characteristics of

the river. Because there was little inter-annual variability in chlorophyll levels in the three rivers, the differences between the mean chlorophyll levels between rivers is therefore likely due to river-specific factors (nutrients and light) and not climatic factors that could affect discharge.

Intra-river variation

It appears that light and nutrients both regulated the variability in chlorophyll levels within the rivers. Both Whalen and Benson (2007) and Koch et al. (2004) found similar results when studying algal production in other riverine systems. Longitudinally, the Ohio river exhibited no consistent pattern of depth, average irradiance, average irradiance dosage or chlorophyll. This was likely due to the Ohio's relatively constant depth throughout its length. Because of the relatively low chlorophyll levels found in the Ohio and its depth, it was likely light limited. One may expect that the upper reaches of the Upper Mississippi were nutrient limited and the lower reaches of the Upper Mississippi were light limited (due to increased urbanization and agriculture in the lower sections). However, there was no obvious difference in nutrient values between the lower and upper reaches of the Upper Mississippi. Though the Upper Mississippi increased in depth towards the mouth of the river and decreased in AI dosage (due to increased velocity), there was no corresponding decrease in chlorophyll values. It is unclear why chlorophyll levels stayed the same when light availability decreased and nutrients concentrations did not change.

The Missouri River had noticeably higher chlorophyll values near the mouth of the river. At the mouth there was also increased depth, increased Kd, increased velocity and therefore decreased Al dosage. This suggests that the Missouri was not just light controlled, but nutrient controlled also. This is illustrated by the observation that there were greater nutrients near the mouth of Missouri (where there is increased primary production) and decreased nutrients near the headwaters of the Missouri (where there is decreased primary production). Basu et al. (2000) reports similar findings from the St Lawrence River: that it is nutrient limited in some areas, and light limited in others. But Knowlton and Jones' (2000) study of the lower Missouri indicated that the Missouri is almost entirely light limited due to high nutrient availability yet low chlorophyll levels.

One thing that is clear from this research is that there are many factors that contribute to the regulation of chlorophyll levels in large river systems, though we were able to illustrate several patterns: that light often controls algal abundance and can be a major part of the explanation of inter-river and intra-river CHLa variation.

Tables

		Ohio	Upper Mississippi	Missouri
Hydrology	Length (km)	1575	2320	3768
	Discharge (m^3/s)	8733	3576	1956
	Basin Area (km^2)	529000	489510	1371017
	Order	9	10	9
	Precipitation (cm/year)	104	96	50
Land Use	Agriculture	48%	70%	33%
	Natural	47%	25%	42%
	Urban	4%	5%	17%
Engineering	Locks and Dams	20, low	26, low	6, high
	Channel Depth (m)	3 at low flow	2.75 at low flow	varies

Table 1: Hydrology, land use and water regulation for the Upper Mississippi, Missouri, and Ohio Rivers. Source: Rivers of North America Benke, Arthur C. and Cushing, Colbert E. Elsiver Academic Press. Amsterdam 2005

	TP (mg/L)	SRP (mg/L)	SiO_2 (mg/L)	TN (mg/L)	$N\text{-}NO_3$ (mg/L)	$N\text{-}NH_4$ (mg/L)
Upper Mississippi	0.17	0.06	4.34	2.35	1.44	0.04
Missouri	0.18	0.03	3.60	1.03	0.47	0.03
Ohio	0.08	0.02	2.42	1.32	0.94	0.04

Table 2: Mean nutrient values from 2004 for the Upper Mississippi, Missouri and Ohio Rivers.

	Upper Mississippi		Missouri		Ohio	
CHLa vs.:	Correlation Coefficient	R squared	Correlation Coefficient	R squared	Correlation Coefficient	R squared
TP	0.23	0.05	0.26	*0.07	0.35	*0.12
SRP	0.43	*0.19	0.28	*0.08	0.18	0.03
SiO_2	0.42	*0.18	0.21	0.04	0.44	*0.19
TN	0.02	0.00	0.34	*0.11	0.50	*0.25
NO_3	0.14	0.02	0.14	0.02	0.40	*0.16
NH_4	0.10	0.01	0.14	0.02	0.17	0.03
Cl^-	0.27	0.07	0.73	*0.53	0.10	0.01

Table 3: Correlation coefficients and R squared values relating Chla concentrations to various nutrient concentrations in the Upper Mississippi, Missouri, and Ohio Rivers. A * denotes an r-squared value that is significant ($p<.05$).

	Ohio	Upper Mississippi	Missouri	River	Year	R*Y	R^2
		Mean +- SE					
CHLa (µg/L)	8.3 ± 1.7*	34.6 ± 1.5*	20.3 ± 1.2*	<0.0001	ns	ns	0.25
Turbidity (NTU)	22 ± 15	42± 12	75.2 ± 10.3	0.006	----	-----	0.65
Depth (m)	6.0 ± 0.2	3.9 ± 0.2	2.7 ± 0.2	<0.0001	-----	-----	0.57
TP (µg/L)	0.08 ± 0.02	0.17 ± 0.02	0.18 ± 0.02	0.002	-----	-----	0.08
SRP (µg/L)	0.02 ± 0.01	0.06 ± 0.00	0.03 ± 0.00	<0.0001	-----	-----	0.22
SiO2 (µg/L)	2.4 ± 0.3	4.4 ± 0.2	3.6 ± 0.2	<0.0001	-----	-----	0.18
TN (µg/L)	1.3 ± 0.1	2.4 ± 0.1	1.0 ± 0.1	<0.0001	-----	-----	0.33
NH4 (µg/L)	0.04 ± 0.00	0.04 ± 0.00	0.03 ± 0.00	<0.0001	-----	-----	0.1
NO3 (µg/L)	0.9 ± 0.1	1.4 ± 0.1	0.5 ± 0.1	<0.0001	-----	-----	0.33
Velocity (m/s)	0.62 ± 0.09	0.68 ± 0.07	1.16 ± 0.06	<0.0001	-----	-----	0.23
AI (µmol photons/s/m^2)	200 ± 78	273 ± 63	490 ± 53	0.003	-----	-----	0.08
Kd (1/m)	2.1 ± 0.9	3.4 ± 0.8	5.4 ± 0.7	0.01	-----	-----	0.06
AI Dosage (mole photons/$m^{2/}$km	0.40 ± 0.20	1.01 ± 0.18	0.56 ± 0.16	0.06#	-----	-----	0.4

Table 4: Mean values for metrics used to characterize light, nutrient and transit time conditions in the Ohio, Upper Mississippi and Missouri Rivers Depth is an average cross-sectional value. Statistical results are for 1-way ANOVAs (main effect = River). * indicates 2-way ANOVA (main effect=River, Year; interaction = R*Y). #indicates a marginally significant value.

Figures

Figure 1: Relationships among variables used to derive the Average Irradiance Dosage (AI Dosage)

Figure 2: Mean CHLa concentration versus rive mile for the Upper Mississippi, Missouri and Ohio Rivers (2004). Note that direction of flow is consistent from left to right in all three panels but the Ohio by convention has zero distance at the headwaters of the river.

Figure 3: General CHLa concentrations by sampling date (2004) and river mile for the Upper Mississippi, Missouri and Ohio Rivers.

Figure 4: General CHLa concentrations by sampling date (2005) and river mile for the Upper Mississippi, Missouri and Ohio Rivers.

Figure 5: Mean depth (m) versus river mile for the Upper Mississippi, Missouri and Ohio Rivers (2004).

Figure 6: Kd versus river mile for the Upper Mississippi, Missouri and Ohio Rivers (2004).

Figure 7: Average irradiance versus river mile for the Upper Mississippi, Missouri and Ohio Rivers (2004). Not scale change in y-axis for the Missouri River.

Figure 8: Velocity (m/s) versus river mile for the Upper Mississippi, Missouri and Ohio Rivers. This was calculated by dividing water discharge by cross sectional area (2004).

Figure 9: Average irradiance dosage (mole photons/m2/km) versus river mile for the Upper Mississippi, Missouri and Ohio Rivers (2004)

Figure 1

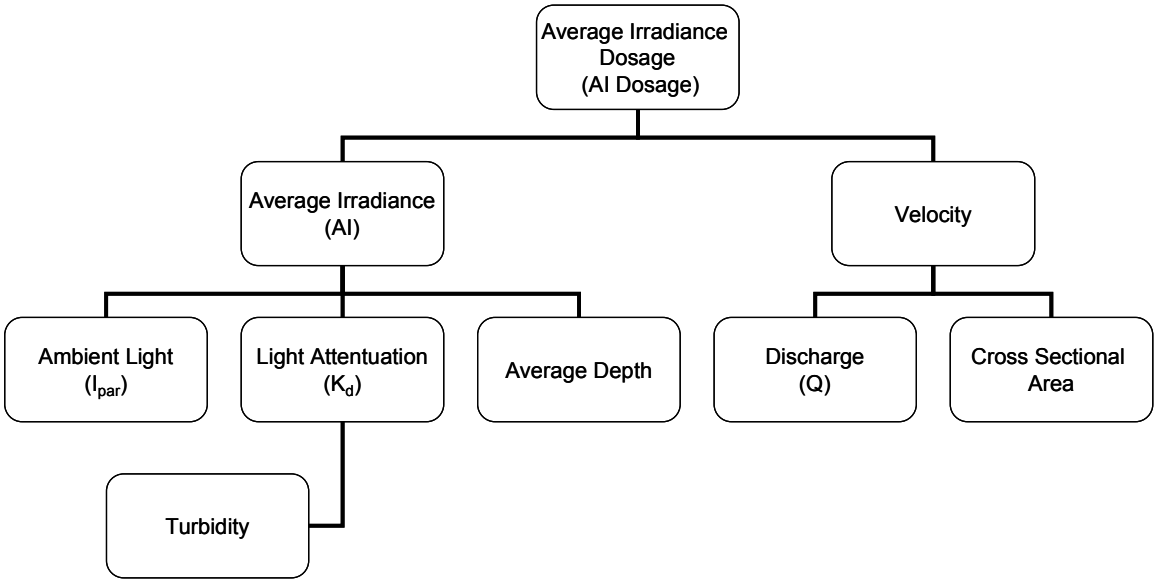

Average Irradiance Dosage (AI Dosage)
Average Irradiance (AI)
Velocity
Ambient Light (I_{par})
Light Attentuation (K_d)
Average Depth
Discharge (Q)
Cross Sectional Area
Turbidity

Figure 2

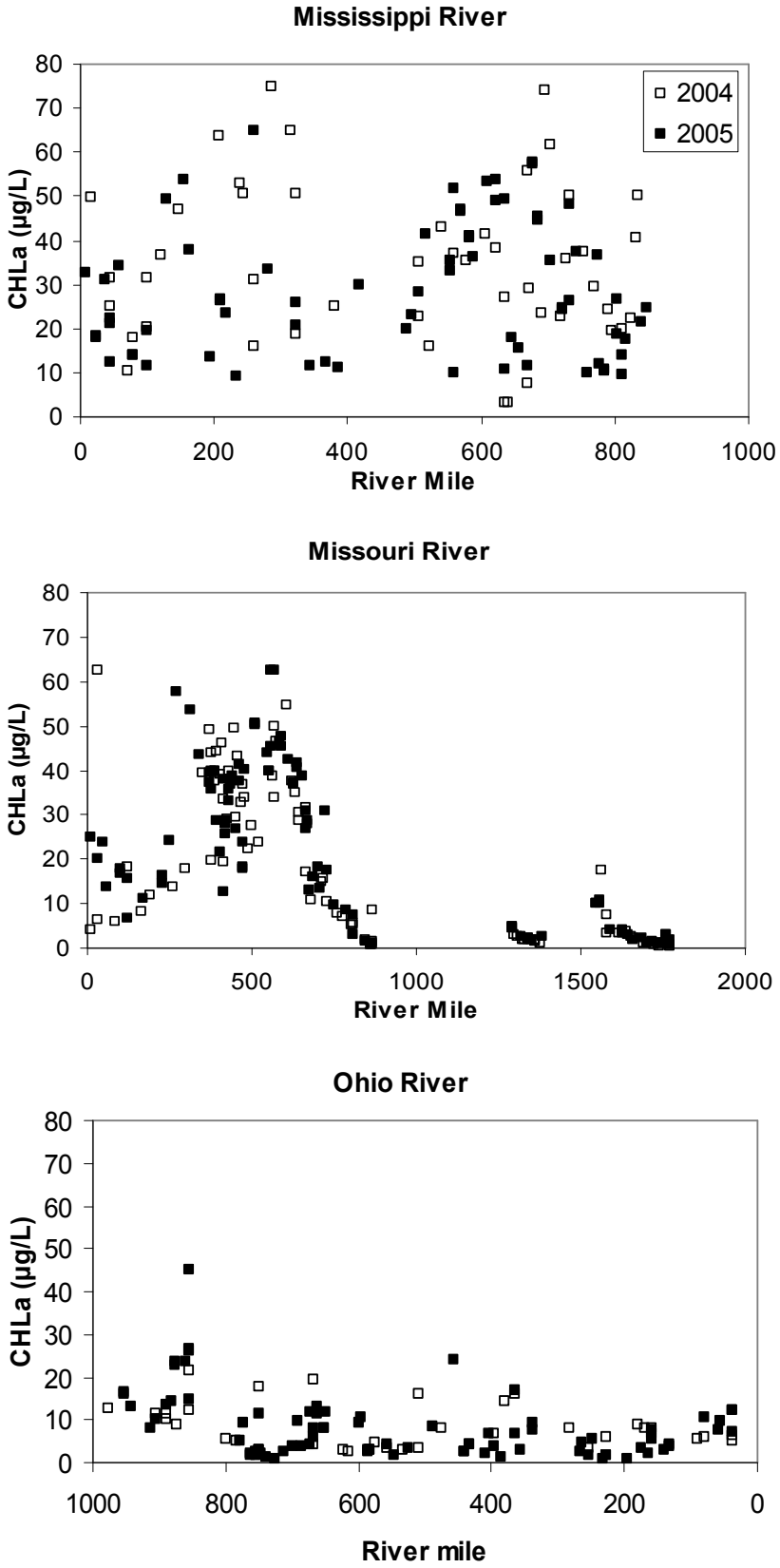
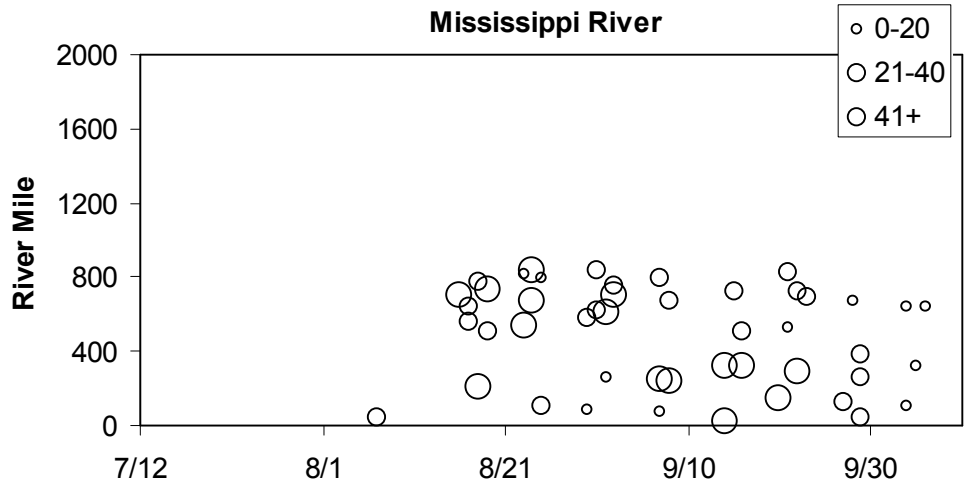
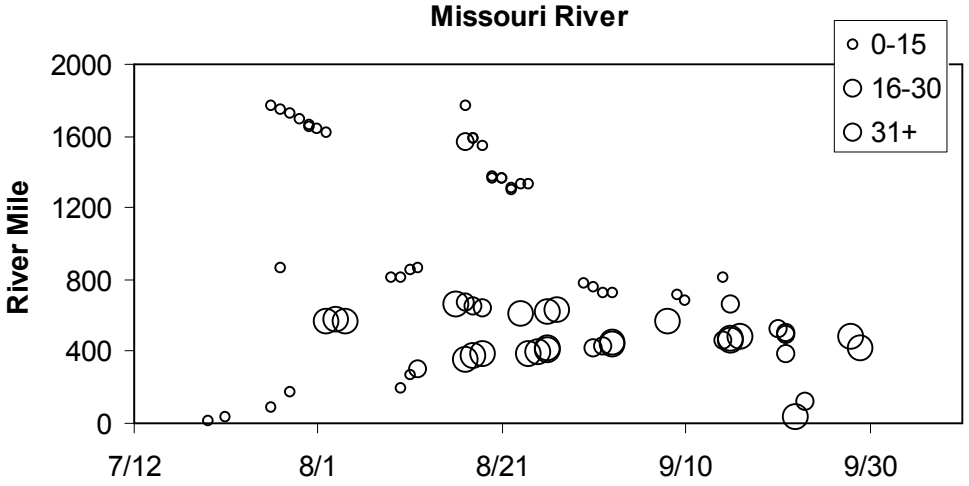

Mississippi River
CHLa (µg/L)
River Mile
2004
2005
Missouri River
CHLa (µg/L)
River Mile
Ohio River
CHLa (µg/L)
River mile

Figure 3


Mississippi River
0-20
21-40
41+
River Mile
2000
1600
1200
800
400
0
7/12
8/1
8/21
9/10
9/30


Missouri River
0-15
16-30
31+
River Mile
2000
1600
1200
800
400
0
7/12
8/1
8/21
9/10
9/30

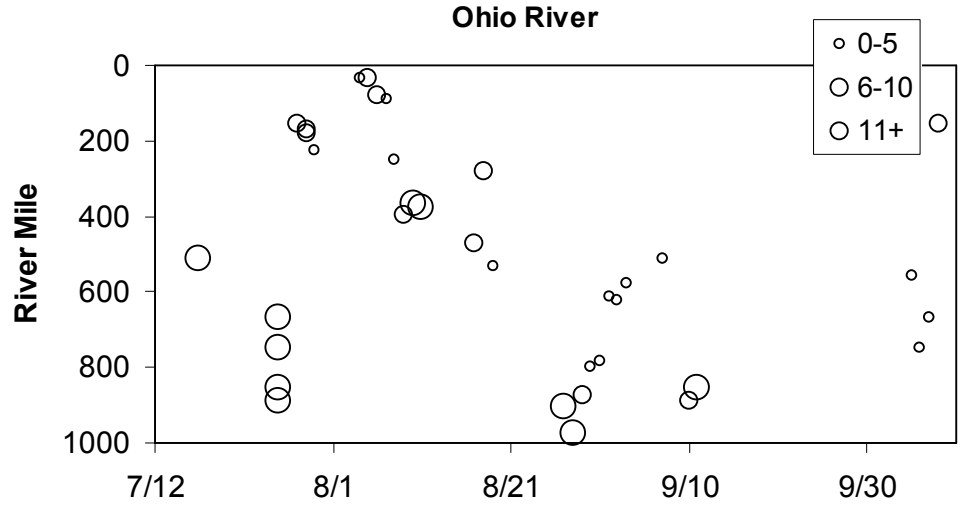

Ohio River
0-5
6-10
11+
River Mile
0
200
400
600
800
1000
7/12
8/1
8/21
9/10
9/30

Figure 4

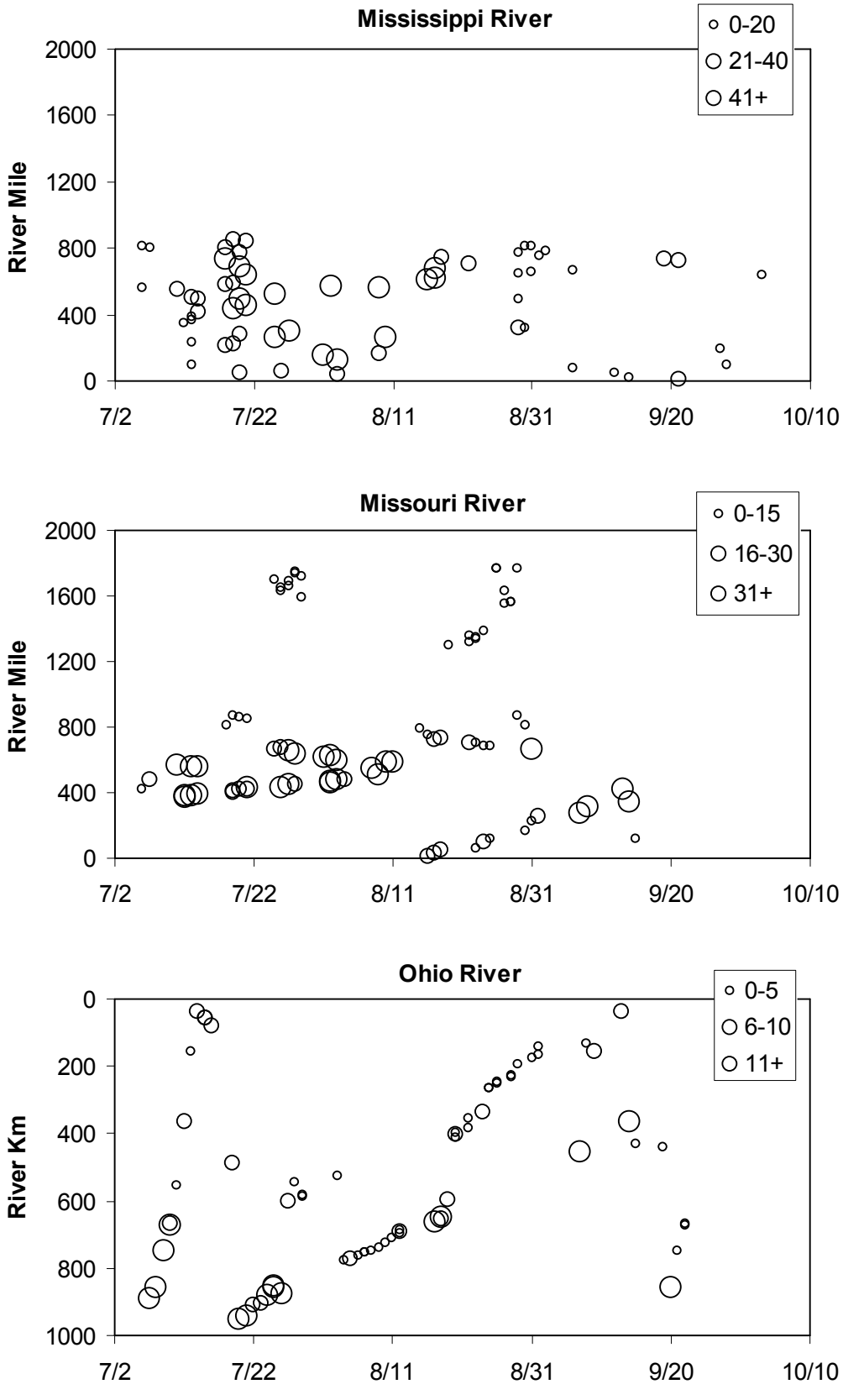
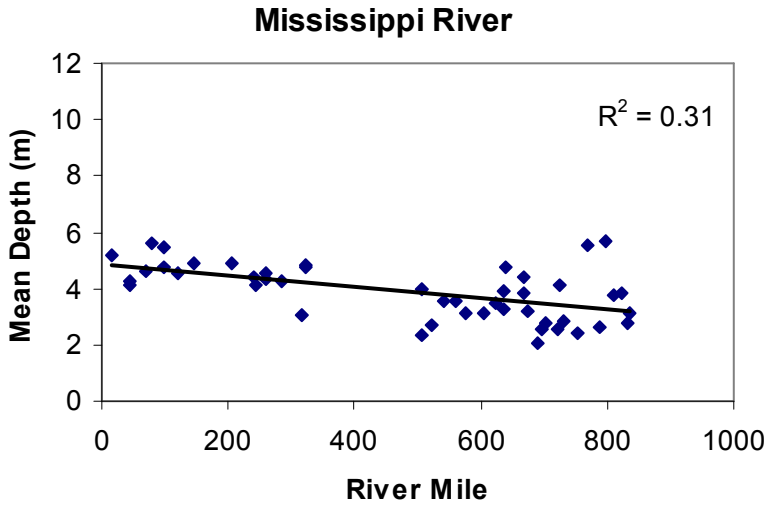
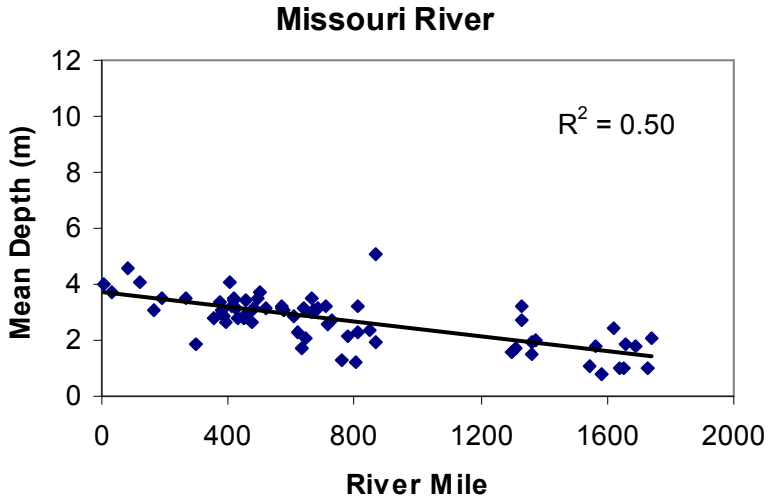

Mississippi River
0-20
21-40
41+
River Mile
2000
1600
1200
800
400
0
7/2
7/22
8/11
8/31
9/20
10/10
Missouri River
0-15
16-30
31+
River Mile
2000
1600
1200
800
400
0
7/2
7/22
8/11
8/31
9/20
10/10
Ohio River
0-5
6-10
11+
River Km
0
200
400
600
800
1000
7/2
7/22
8/11
8/31
9/20
10/10

Figure 5


Mississippi River
Mean Depth (m)
River Mile
R2 = 0.31
0
2
4
6
8
10
12
0
200
400
600
800
1000


Missouri River
Mean Depth (m)
River Mile
R2 = 0.50
0
2
4
6
8
10
12
0
400
800
1200
1600
2000

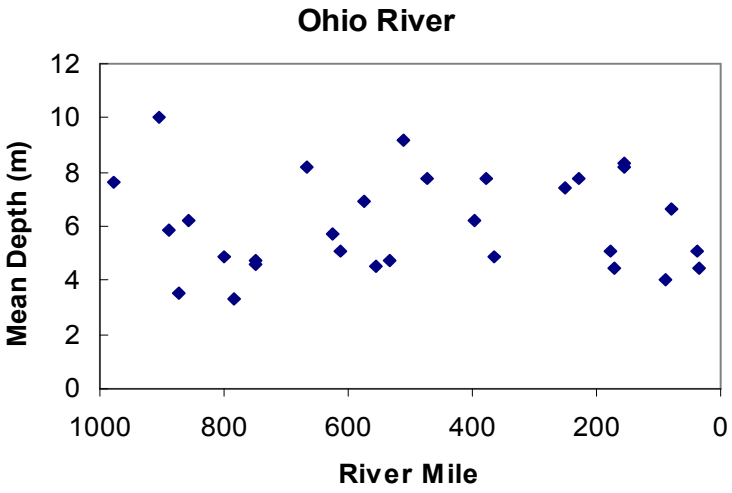

Ohio River
Mean Depth (m)
River Mile
0
2
4
6
8
10
12
1000
800
600
400
200
0

Figure 6

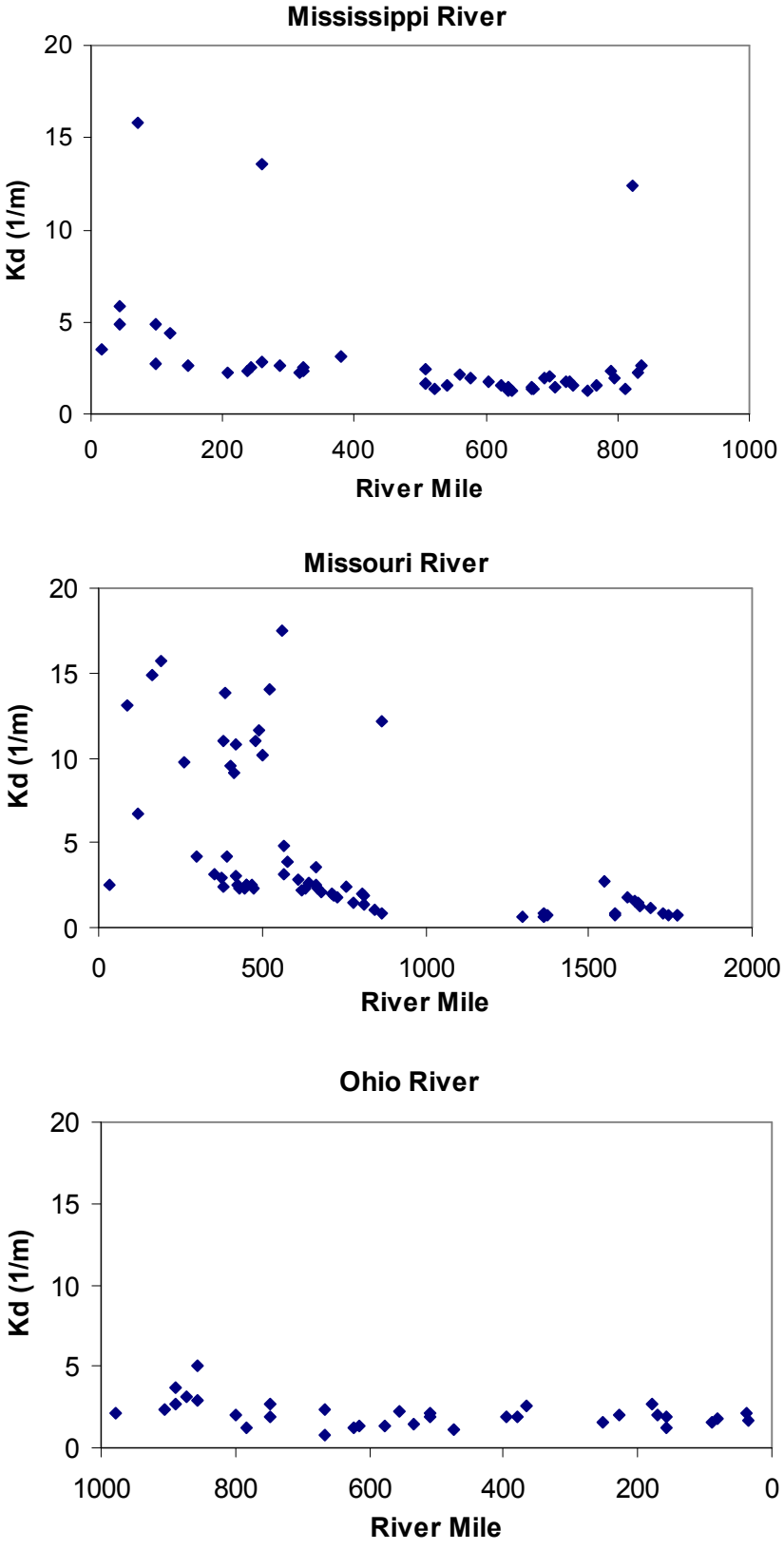

Mississippi River
Kd (1/m)
River Mile
0
5
10
15
20
0
200
400
600
800
1000
Missouri River
Kd (1/m)
River Mile
0
5
10
15
20
0
500
1000
1500
2000
Ohio River
Kd (1/m)
River Mile
0
5
10
15
20
1000
800
600
400
200
0

Figure 7

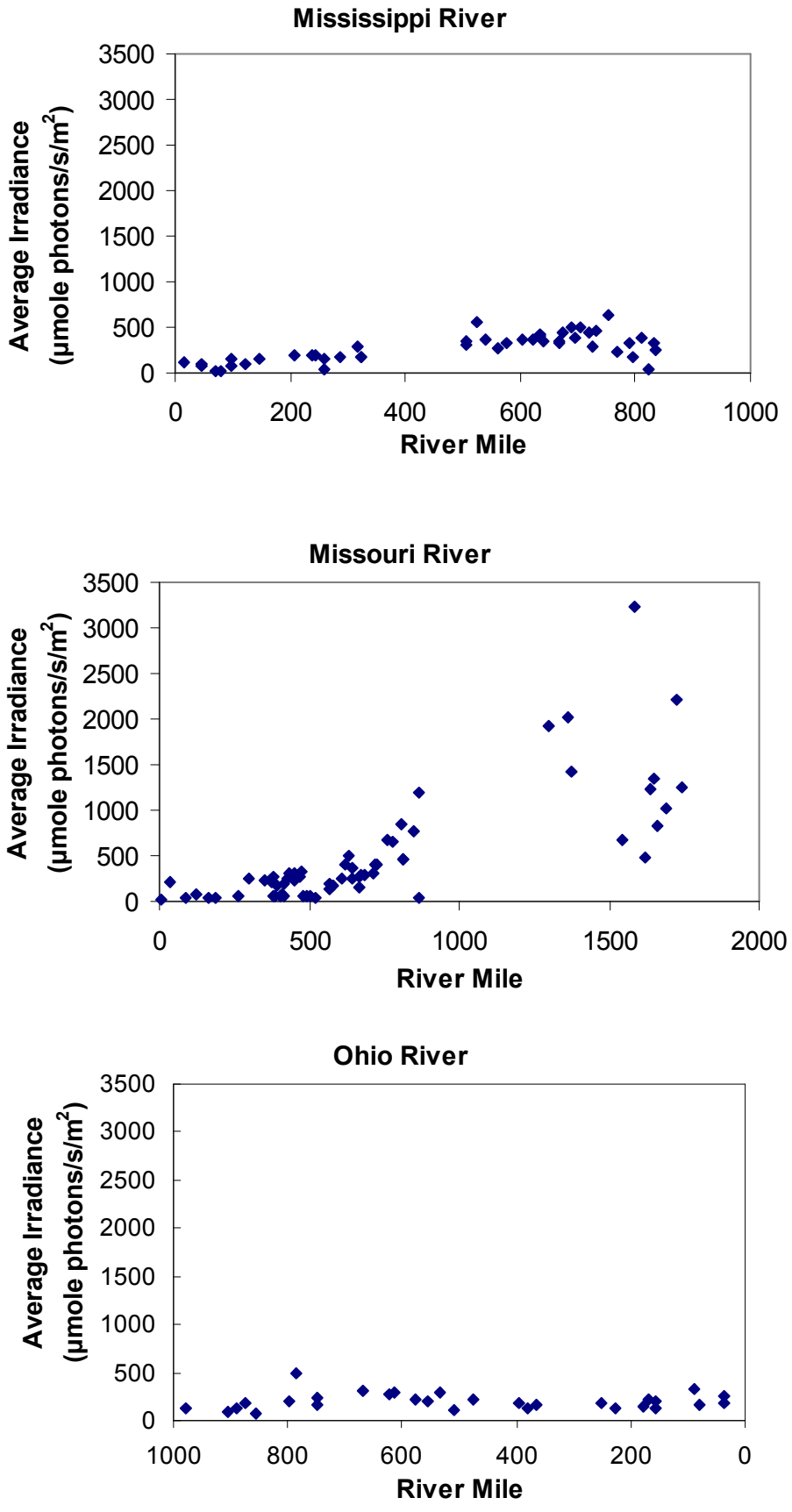
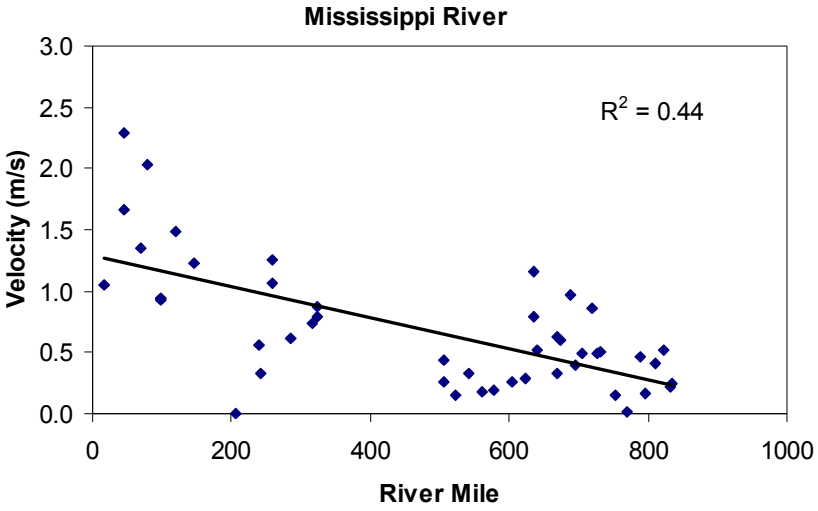
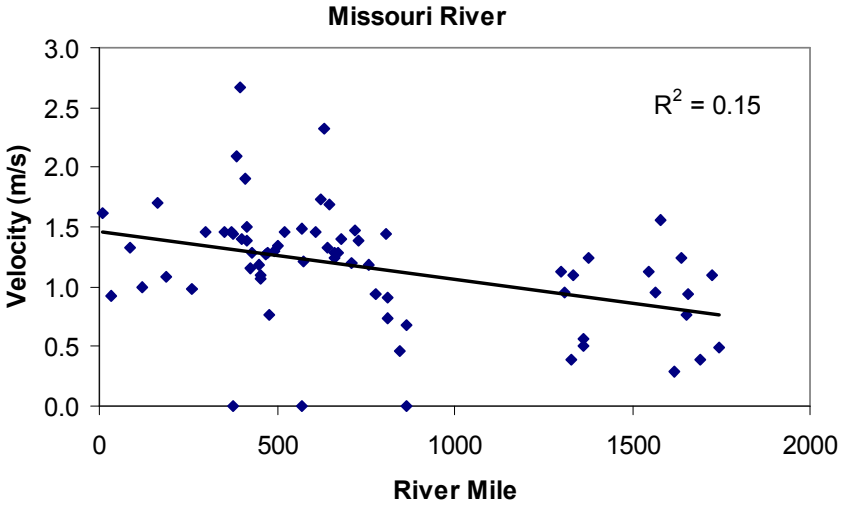

Mississippi River
Average Irradiance (µmole photons/s/m2)
3500
3000
2500
2000
1500
1000
500
0
0
200
400
600
800
1000
River Mile
Missouri River
Average Irradiance (µmole photons/s/m2)
3500
3000
2500
2000
1500
1000
500
0
0
500
1000
1500
2000
River Mile
Ohio River
Average Irradiance (µmole photons/s/m2)
3500
3000
2500
2000
1500
1000
500
0
1000
800
600
400
200
0
River Mile

Figure 8


Mississippi River
R^2 = 0.44
Velocity (m/s)
River Mile
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0
200
400
600
800
1000


Missouri River
R^2 = 0.15
Velocity (m/s)
River Mile
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0
500
1000
1500
2000

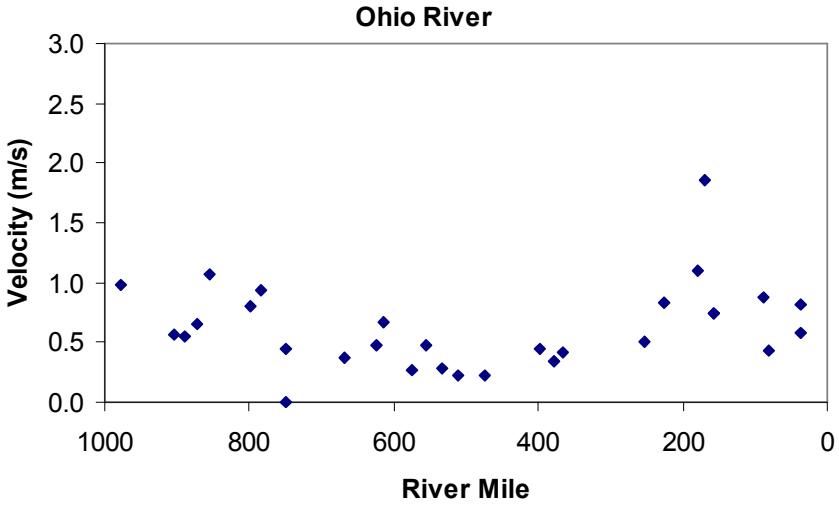
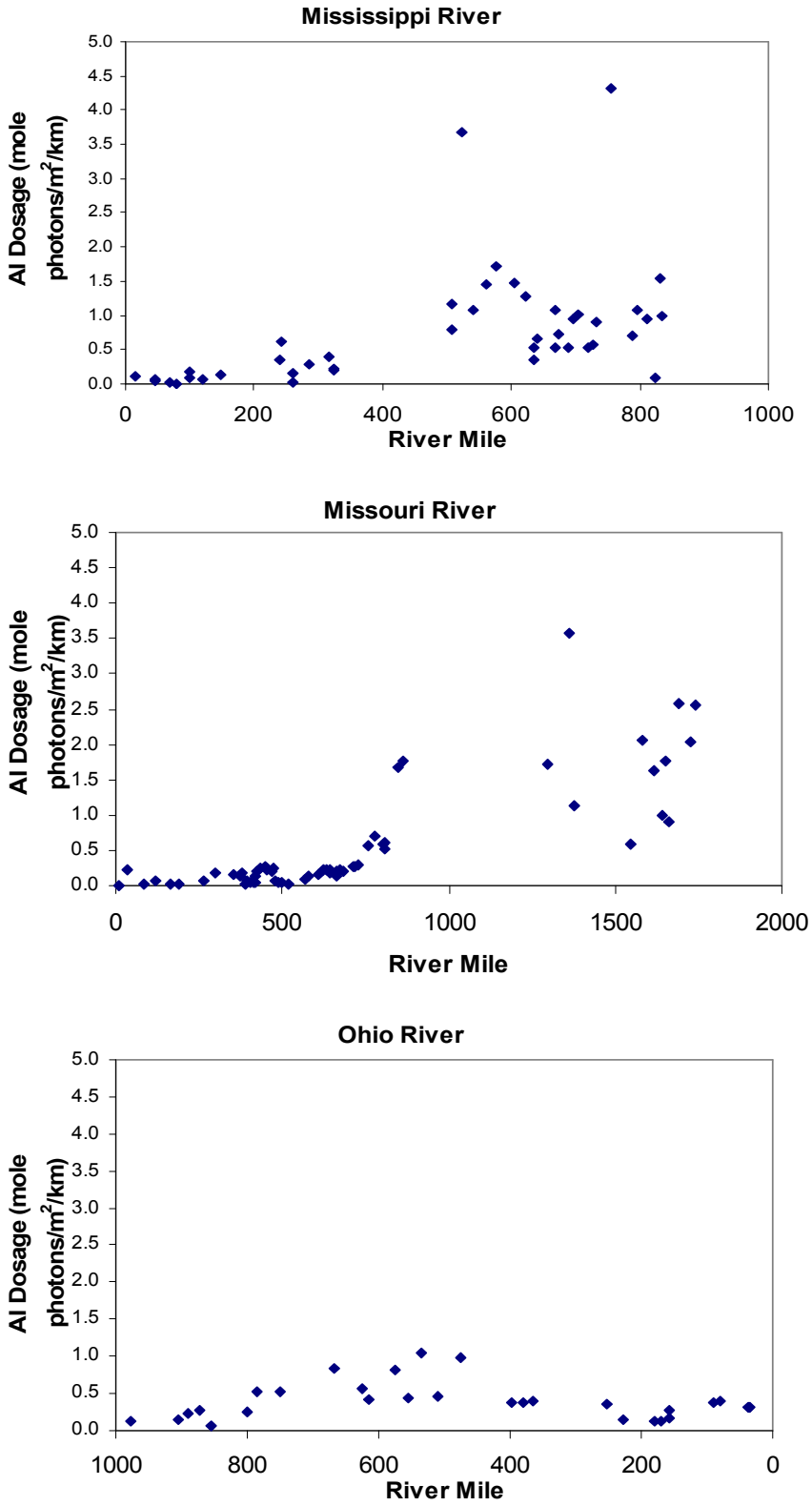

Ohio River
Velocity (m/s)
River Mile
0.0
0.5
1.0
1.5
2.0
2.5
3.0
1000
800
600
400
200
0

Figure 9


Mississippi River
Al Dosage (mole photons/m2/km)
River Mile
Missouri River
Al Dosage (mole photons/m2/km)
River Mile
Ohio River
Al Dosage (mole photons/m2/km)
River Mile

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